

RESEARCH

Agronomic Feasibility of a Continuous Double Crop of Winter Wheat and Soybean Forage in the Southern Great Plains

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ABSTRACT

In the southern Great Plains, dryland double-cropping soybean [*Glycine max* (L.) Merr.] after winter wheat (*Triticum aestivum* L.) could provide quality summer forage, partially offset mineral fertilizer N applied to winter wheat, and lessen soil erosion. Waiting for wheat grain to mature, however, delays soybean planting and subjects growth to dry and hot conditions. Planting soybean after a hay crop of wheat was investigated to determine the feasibility of the system as a source of livestock feeds and N uptake by both crops. Twelve treatment combinations of two wheat fertilizer N levels (0 and 112 kg N ha⁻¹) and six summer management treatments (fallow: conventional and no-till; soybean: grazed, cut for hay, green manure, and mulch) were arranged in strips across four replications. Soybean biomass ranged from 1.35 to 1.90 Mg ha⁻¹ when soybean grazing and harvest occurred at seed fill, and crude protein ranged from 129 to 220 g kg⁻¹ resulting in a 3-yr average N uptake of 44 kg ha⁻¹. Within each N fertilizer level, average wheat forage yields were not different, but yield increased 29% with N fertilizer and crude protein was inversely related to yield. Double-cropped soybean failed to offer any yield-enhancing N benefit to wheat or enhance soil N and C content after 3 yr, even when used as a green manure. Unless a producer is willing to accept the low productivity of soybean as a double crop with wheat, the feasibility of this dryland double-crop forage system is limited.

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Abbreviations: CT, conventional tillage; MG, maturity group; NT, no tillage.

WINTER WHEAT (*Triticum aestivum* L.) planted in the southern Great Plains is grown extensively for forage as well as a grain-only crop (Pinchack et al., 1996; Hossain et al., 2004). Most of the wheat used as forage is grazed from mid-November until early March as a dual-purpose crop (graze plus grain) or from mid-November until early May as full-season pasture. Shortly after heading around mid-April, some producers will cut wheat for a hay crop or silage. After wheat harvest, land is traditionally kept fallow during the summer, using tillage to reduce stubble and control weeds. Sources of summer pasture are mostly native or improved warm-season perennial grasses, although annual warm-season grass may also be used (Dalrymple, 1999). Early in the season, crude protein quality of these perennial grasses is quite good for stocker livestock production, but crude protein concentrations decline as the grasses mature (Perry and Baltensperger, 1979; Mitchell et al., 2001; Arthington and Brown, 2005). Planting a summer annual legume after wheat could provide additional high-quality forage after warm-season grasses begin to decline in quality, provide groundcover to lessen soil erosion, and perhaps

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provide an organic source of N to partially offset mineral fertilizer N required to produce a wheat crop.

Before 1941, soybean [*Glycine max* (L.) Merr.] was primarily grown in the USA as a hay crop. Recently there has been a resurging interest in the use of soybean as an annual forage crop in the USA with the release of several forage types (Devine et al., 1998a, 1998b; Devine and Hatley, 1998; Devine and McMurtrey, 2004). Forage evaluations of standard and forage soybean types in the Midwest (Sheaffer et al., 1992; Hintz et al., 1992; Readfern et al., 1999; Sheaffer et al., 2001) and southern Great Plains (Heitholt et al., 2004; Rao et al., 2005) are promising, and while double-cropping a winter cereal and forage soybean may be feasible for the Midwest (Sheaffer et al., 1992), dryland production of soybean after wheat grown for grain in Oklahoma is uncertain (Keim et al., 2003; Rao et al., 2005) given the variable spring and summer rainfall patterns of the southern Great Plains.

According to Keim et al. (2003), unfavorable environmental conditions immediately after the harvest of wheat grain is a critical factor in the production risk of a dryland continuous wheat-soybean double-crop system in Oklahoma. Changing a double-crop system of wheat grown for grain followed by soybean to one that harvests wheat as a hay crop or full-season pasture would allow soybean planting up to 6 wk earlier and leave more soil water (Brown, 1971; Musick et al., 1994) for the soybean crop. Consequently, we investigated the performance of soybean and its impact on productivity of a winter wheat hay crop grown with and without mineral N fertilizer using conventional tillage (CT) and no-tillage (NT) practices. Our research objectives were to assess the feasibility of this dryland double-crop system as a source of livestock feeds by measuring the quantity and quality of soybean forage and to compare the effects of using soybean for grazing, as a hay crop, or as a cover crop on the production and N accumulation of a winter wheat hay crop.

MATERIALS AND METHODS

Location and Previous Cropping

Experimental plots were located at the Grazinglands Research Laboratory near El Reno, OK (35.56932 lat;-98.04455 long), on a Norge silt loam (fine-silty, mixed, active, thermic, Udic Paleustoll). The site (1.2 ha) was a winter wheat field that was harvested for grain in early June 1999. Wheat stubble was disked after grain harvest, and disked twice more before planting at the end of June with pigeon pea [*Cajanus cajan* (L.) Millsp.] intended for a grazing trial, but Holstein steers (*Bos taurus* L.) preferentially grazed the abundant pigweed (*Amaranthus* spp.) and crabgrass (*Digitaria* spp.), leaving the pigeon pea mostly ungrazed. In mid-October 1999, pigeon pea was swathed, baled, and removed from the site before disking. Nitrogen fertilizer treatment plots of 0 and 112 kg N ha⁻¹ (N0 and N1, respectively) were created by incorporating granular urea before planting winter wheat (cv. Jagger; 112 kg seed ha⁻¹). Each N treatment plot was 14.6 m wide by 79.1 m long, arranged in a randomized complete block design

and replicated four times with 9.8 m alleys between blocks. Alleys were planted with winter wheat but not fertilized with N. Wheat grain was harvested in early June 2000, wheat stubble burned, and pigeon pea NT planted. Because of poor pigeon pea emergence and intense weed pressure, the site was disked in early August. The site was disked and dragged with a harrow, fertilizer N applied to the same plots as before, dragged with a harrow to incorporate the fertilizer, and planted with Jagger winter wheat as before. In early May 2001, winter wheat at anthesis was cut for hay. Hay yield (dry wt.) from the N0 treatment was 7.09 Mg ha⁻¹, which was significantly less ($P < 0.05$) than the 7.91 Mg ha⁻¹ from the N1 treatment.

Summer Management Treatments

Using the existing plots, management treatment plots were randomly assigned as strip plots across the two N treatments. Six management treatments included both CT and NT practices within each replicate of the N strips. The treatments were summer fallow CT, summer fallow NT, soybean grazed NT, soybean hay NT, soybean cover crop CT (green manure), and soybean cover crop NT (mulch). Plot size was 14.6 × 7.9 m except for grazed NT plot size, which was 14.6 × 39.6 m. Three successive double crops of soybean followed by winter wheat were evaluated in 2001/2002 (Year 1), 2002/2003 (Year 2), and 2003/2004 (Year 3). Each year after harvest of the Jagger winter wheat hay crops (during third week of April just after anthesis), all plots were sprayed with glyphosate [N-(phosphonomethyl)glycine; 1.5–3.1 kg a.i. ha⁻¹, depending on year] for weed control before planting glyphosate-resistant soybean (late Maturity Group [MG] IV in Year 1 [Garst 4888RR] and Year 2 [Garst 472RR]; Garst, late MG III in Year 3 [Midland 9G380RR/STS]). Soybean seeds (73 kg ha⁻¹) treated with *Bradyrhizobium japonicum* inoculant were planted in 40-cm rows with a NT drill during the middle of May. The first of at least two disk operations of the summer fallow CT plots occurred immediately after soybean was planted. Summer annual weeds in the NT treatments were controlled with one or more applications of glyphosate (1.5–2.5 kg a.i. ha⁻¹, depending on year). Soybean aboveground biomass measurements were made just before grazing commenced for a 2- to 3-wk period beginning mid-July to mid-August. Plots intended for hay harvest and plants in unfenced alley areas were cut with a small plot forage harvester (Hege 212, Wintersteiger, Inc., Salt Lake City, UT) and the biomass removed. Soybean plants in the green manure and mulch plots were cut with a sickle bar mower (Troy-Bilt model 34063, MTD Consumer Group, Inc., Cleveland, OH), and the biomass in the green manure plots was incorporated into the soil with disking. After termination of grazing, the remaining soybean crop (mainly stems) was cut with a flail mower (John Deere 370, John Deere, Moline, IL). Early to mid-September all plots were sprayed with glyphosate for weed control, and the CT plots were disked before planting Jagger winter wheat seed (112 kg ha⁻¹) in 20-cm rows with a NT drill between late September and early October. Mid-November each year the N1 plots received broadcast applications of granular urea at 112 kg N ha⁻¹.

Forage Measurements

Measurements of aboveground biomass of soybean plants were obtained either by hand harvesting or use of a small plot forage

harvester. Two sets of 20 randomly selected plants in each graze NT, green manure, and mulch plot were clipped to a stubble height of 5 cm, oven-dried to constant weight in a forced-air oven at 65°C, weighed, and then ground in a cyclone mill for N analysis. Soybean plant density in each of these plots based on the number of plants in two randomly selected rows, each 1.5 m long, was used to convert the weight of clipped plants into biomass yields. A small plot forage harvester was used to obtain soybean forage biomass measurements for the hay NT plots. Two passes through each plot with the harvester removed 16.4 m² each pass and left a stubble height of 5 cm. For each harvester pass, the harvester weighed the cut soybean hay and a composite subsample was collected and the fresh weight measured in the field before processing for dry weight and N analysis as described above for the hand-harvested soybean plants. Moisture content of the subsample was used to calculate the dry weight of forage obtained with the small plot harvester. The small plot forage harvester was used to obtain wheat hay biomass as described for the soybean hay harvests. Soybean and wheat oven-dried samples were measured for total N using an automated flash-combustion analyzer (LECO CHN1000; Leco Corp., St. Joseph, MI). Both of the two subsamples from each plot were analyzed for total N. Forage crude protein values were calculated by multiplying total N concentration by 6.25.

Soil Measurements

A hand-held soil probe was used to collect soil samples (2.5-cm-diameter cores) for the 0- to 15-cm and the 15- to 30-cm depths. About 25 to 30 cores were taken from each plot and combined by depth within a plot and air-dried for analysis. The Soil, Water, and Forage Analytical Laboratory at Oklahoma State University, Stillwater, analyzed samples collected mid-July 1999. The 0- to 30-cm depth contained about 35 ± 4 kg nitrate N ha⁻¹ and had nondeficient P and K soil test indexes of 214 ± 41 and 1310 ± 100 , respectively (means \pm SE of the four replicated blocks). Soil samples were collected as before in mid-July 2004 and air-dried, crushed to pass a 2-mm screen, then extracted with 1 N KCl and analyzed by flow injection (FIAstar 5010 Analyzer, Foss North America, Inc., Eden Prairie, MN) for ammonium N (AN 50/84; Tecator 1984) and nitrate N (AN

62/83; Tecator 1983). Soil total N and C in air-dried samples were measured using an automated combustion analyzer (Vario-Max, Elementar Americas, Inc., Mt. Laurel, NJ). The July 1999 samples from the 0- to 15- and 15- to 30-cm depths contained 0.79 ± 0.03 and 0.68 ± 0.02 g total N kg⁻¹ soil, respectively, and 8.32 ± 0.33 and 7.21 ± 0.22 g total C kg⁻¹ soil, respectively (means \pm SE of the four replicated blocks).

Statistical Analyses

Experimental subunits (N fertilizer treatments and summer management treatments) were arranged in strips across each replication. Both subunits were randomized independently with each replication. Because the arrangement of plots remained the same across three successive double crops, the data were analyzed using a mixed linear model with repeated measures (PROC MIXED) (Littell et al., 1996; SAS Institute, 2005). Replicates and interaction terms with replicate were considered random terms, and all other terms (year, N fertilizer treatment, soybean management treatment) were considered fixed for the ANOVA of soybean and wheat traits. The ANOVA of soil traits was conducted by year using PROC MIXED. Replicates and interaction terms with replicate were considered random terms, and N fertilizer and soybean management treatment factors were considered fixed for the ANOVA of soil traits. Pairwise comparisons of least-square means obtained with the PDIF option were sorted with the pdmix800 macro developed by Saxton (Saxton, 1998).

RESULTS AND DISCUSSION

Precipitation for each of the 3 yr of the study was less than or nearly equal that of the 1994 through 2005 average of 814 mm yr⁻¹ recorded at a Mesonet station within 3 km of the research plots. Yearly precipitation deficits from the 12-yr average were 207 mm in 2001, 23 mm in 2002 and 339 mm in 2003. There were marked differences in the monthly precipitation distribution patterns from the 12-yr average (data not shown), and there were substantial precipitation deficits for the interval between harvest of wheat as a hay crop and the beginning of grazing and cutting the soybean crop: 67 mm (-21%) for

Table 1. Significance ($P > F$) values from the ANOVA of biomass, crude protein concentration, and aboveground N accumulation of soybean and winter wheat forage crops from three successive double-crop sequences.

Effect [†]	Soybean			Winter wheat		
	Biomass	Crude protein	N accumulated	Biomass	Crude protein	N accumulated
	$P > F$					
Nitrogen (N)	0.6698	0.0072	0.6147	0.0087	<0.0001	<0.0001
Treatment (T)	0.0582	0.0393	0.1474	0.2269	0.0240	0.0393
N \times T	0.2790	0.2721	0.1918	0.0186	0.0692	0.8888
Year (Y)	<0.0001	<0.0001	0.0124	<0.0001	<0.0001	<0.0001
N \times Y	0.0075	<0.0001	0.1052	0.0072	0.0004	<0.0001
T \times Y	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	0.0005
N \times T \times Y	0.4821	0.3571	0.1880	0.0817	0.9382	0.2142

[†]Nitrogen, two levels of 0 and 112 kg N ha⁻¹ applied to winter wheat; treatment, six management levels consisting of summer fallow with conventional tillage, summer fallow with no-tillage, no-till soybean grazed, no-till soybean hay, green manure crop of no-till soybean, and mulch crop of no-till soybean; year, three consecutive years.

114 d in 2001, 183 mm (-51%) for 123 d in 2002, and 123 mm (-44%) for 81 d in 2003. Compared to the 12-yr daily average, total precipitation between planting and harvest of wheat as a hay crop was 114 mm less (-31%) in 2001/2002 (Year 1), 2 mm more (+ 0.6%) in 2002/2003 (Year 2), and 71 mm less (-20%) in 2003/2004 (Year 3).

Summer management treatment effects were observed on soybean biomass, soybean and wheat protein concentration, and N accumulated by wheat forage (Table 1). Fertilizer N impacted all three wheat forage traits but only affected soybean protein concentration. We anticipated that

Table 2. Biomass, forage crude protein, and aboveground N accumulated by soybean and wheat crops for three successive double-crop sequences (Year 1, 2001/2002; Year 2, 2002/2003; Year 3, 2003/2004). Management treatments \times year effect means ($n = 8$) were averaged across two N fertilizer treatments (N0 and N1, 0, and 112 kg N ha⁻¹, respectively). Values for the soybean crop were at initiation of grazing and those of the wheat crop were at hay harvest. Year 1, 2, and 3 growing season precipitation differences from a 12-yr average were -21, -51, and -44% for soybean and -31, +0.6, and -20% for wheat, respectively.

Treatments [†]	Biomass			Crude protein			N accumulated		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
	Mg ha ⁻¹			g kg ⁻¹			kg ha ⁻¹		
Soybean									
Graze NT	1.56bc [‡]	1.88abc	1.36c	143fg	183cd	203ab	35.2bc	53.6a	43.6abc
Soy hay NT	1.13c	1.46c	1.18c	152ef	205abc	216a	26.5c	46.5ab	40.4abc
Soy manure	2.40ab	1.66abc	1.55bc	136fg	169de	220a	49.7ab	43.1abc	52.3ab
Soy mulch	2.52a	1.62bc	1.32c	129g	183bcd	213a	51.2ab	45.6abc	44.5abc
Mean	1.90A	1.65B	1.35C	140C	185B	213A	40.7B	47.2A	45.2AB
Winter wheat									
Fallow CT [†]	6.92b–f	6.26c–h	9.25a	144abc	136b–e	120c–g	163a–d	137a–e	178a
Fallow NT	4.46h	7.65abc	8.44ab	167a	129b–f	110efg	118de	159a–d	153a–e
Graze NT	5.41e–h	7.11bcd	7.79abc	139bcd	117c–g	96g	122b–e	135a–e	122b–e
Soy hay NT	5.27fgh	6.93b–e	8.44ab	153ab	122c–g	103fg	133a–e	137a–e	143a–e
Soy manure	5.59d–h	5.71d–h	8.91a	133b–e	134b–e	117c–g	123b–e	123b–e	169ab
Soy mulch	5.00gh	6.52c–g	8.16ab	137b–e	122c–g	97g	113ef	129b–e	131a–e
Mean	5.44C	6.70B	8.50A	145A	127B	107C	129B	136B	150A

[†]CT, conventional tillage; NT, no tillage.

[‡]Values of a trait within a crop followed by the same lowercase letter are not significantly different at $P = 0.05$. Main effect values of a trait within a crop followed by the same uppercase letter are not significantly different at $P = 0.05$.

the level of applied N to wheat would affect how the soybean forage traits responded to cultural practice, but the N application \times summer management treatment interaction was not significant. The N application \times summer management treatment did affect wheat biomass production, but not the other two wheat forage traits. Nearly all year \times summer treatment interactions and year \times N rate interactions were significant for both soybean and wheat forage traits. Forage biomass, crude protein, and above-ground N accumulation for the three-way interaction of winter wheat N application \times summer management treatment \times year were not significant for either soybean or winter wheat crops.

Soybean Forage Responses

Biomass

The N benefit, soil protection advantage, and nutritive feed merit of a soybean double-cropped forage system with winter wheat will depend on the amount of soybean biomass produced. The source of the significant summer management treatment \times year interaction for soybean biomass was due to inexplicably low NT treatment values in Year 1. Overall yearly means of soybean biomass at R5 growth stage (Fehr and Caviness, 1977) ranged from 1.35 to 1.90 Mg ha⁻¹ (Table 2). The lowest biomass value was for a late MG III cultivar at 62 d after planting (Year 3), and the highest for a late MG IV cultivar at 93 d after planting (Year 1). These levels of biomass production were substantially less than the 3.5 to 4.6 Mg ha⁻¹ forage yields

at about 90 d after planting of non-double-cropped grain- and forage-type soybean in the Northern Texas Blacklands region of the southern Great Plains (Heitholt et al., 2004), but fell within the biomass range of 0.7 to 2.3 Mg ha⁻¹ at about 92 d after planting for grain- and forage-type soybean grown after harvesting wheat for grain at a location close to our study (Rao et al., 2005). In a more favorable environment than encountered in the dryland crop production regions of the southern Great Plains, soybean forage yield in the upper Midwest averaged 5.7 Mg ha⁻¹ for grain-type varieties at growth stage R5 (Hintz et al., 1992), and 9.2 Mg ha⁻¹ for grain and forage types at stages R4 (full pod at one of the four uppermost nodes of the main stem) to R6 (full seed at one of the four uppermost nodes of the main stem) (Sheaffer et al., 2001).

Crude Protein

Differences in soybean crude protein concentrations among summer management treatments within years were unexpected, as was the wide range of values from 129 to 220 g kg⁻¹ across the 3 yr (Table 2). Crude protein concentration differences may be partially attributed to biomass differences and the partitioning of dry matter between leaf and stem tissues. For example, concentration of forage crude protein for the soybean hay NT treatment tended to be numerically greater but had the numerically lowest biomass among treatments within a year (Table 2). Soybean leaves can have a twofold greater N concentration than stems (Hintz



Figure 1. Appearance of soybean plants after termination of grazing by cattle. Grazing of plants in the left photograph began after growth stage R5; soybean pods are absent from plants when grazing began before growth stage R3 (beginning pod), as illustrated in the right photograph from a different experiment.

and Albrecht, 1994; Sheaffer et al., 2001; Rao et al., 2005). The variety of soybean used in Year 3 (late MG III) was not the same as the one used in Year 1 and Year 2 (late MG IV) and may have contributed to the difference in forage crude protein even though samples were collected each year shortly after stage R5 had begun. Among grain-type soybean cultivars ranging from MG II to MG V, significant differences in the

N concentrations of plant parts sampled at stage R5 occurs (Zeiher et al., 1982). Yearly overall values of crude protein concentration we measured were consistent (Hintz et al., 1992; Sheaffer et al., 2001) or slightly greater (Heitholt et al., 2004) than those reported for grain-type soybean at a similar growth stage and exceeded the requirement for stocker livestock feed (National Research Council, 1984). The crude protein concentration of grazed soybean would likely be greater because cattle primarily consumed leaves rather than stems and pods (Fig. 1).

The interaction of winter wheat N application \times summer management treatment was not significant for the soybean traits measured (Table 1 and Table 3). However, the main plot effect of N application to winter wheat and the subplot effect of soybean management had a significant effect on soybean crude protein concentration. Averaged across all years, crude protein of NT soybean hay was increased following wheat

fertilized with 112 kg N ha⁻¹ (Table 3).

Nitrogen Accumulation

In general, both N application and summer management had little or no effect on soybean N accumulation. Above-ground N accumulation by soybean had a significant summer management treatment \times year interaction (Table 1) that was attributed to differences among treatments only in

Table 3. Biomass, forage crude protein, and aboveground N accumulated by soybean and wheat that was harvested for hay. Management treatments \times N fertilizer (N0 and N1, 0, and 112 kg N ha⁻¹, respectively) means ($n = 12$) were averaged across three successive double-crop sequences. Values for the soybean crop were at initiation of grazing.

Treatments [†]	Biomass			Crude protein			N accumulated		
	N0	N1	Mean	N0	N1	Mean	N0	N1	Mean
	Mg ha ⁻¹			g kg ⁻¹			kg ha ⁻¹		
Soybean									
Graze NT	1.59a [‡]	1.61a	1.60A	167a	186a	176B	41.7a	46.6a	44.1A
Soy hay NT	1.17a	1.34a	1.25A	184a	199a	191A	34.3a	41.3a	37.8A
Soy manure	2.05a	1.69a	1.87A	160a	190a	175B	49.6a	47.1a	48.4A
Soy mulch	1.88a	1.76a	1.82A	166a	184a	175B	47.8a	46.4a	47.1A
Mean	1.67A	1.60A		169B	190A		43.3A	45.4A	
Winter wheat									
Fallow CT	6.88b–e	8.07a	7.47A	116a	150a	133AB	125bc	193a	159A
Fallow NT	6.29b–e	7.41a–d	6.85A	112a	158a	135A	107c	180a	144AB
Graze NT	5.74de	7.80ab	6.77A	105a	129a	117B	95c	158ab	126AB
Soy hay NT	5.82de	7.94ab	6.88A	111a	141a	126AB	101c	175a	138AB
Soy manure	5.92de	7.56abc	6.74A	111a	146a	128AB	100c	176a	138AB
Soy mulch	5.33e	7.79ab	6.56A	104a	133a	119AB	85c	163a	124B
Mean	6.00B	7.76A		110B	143A		102B	174A	

[†]CT, conventional tillage; NT, no tillage.

[‡]Values of a trait within a N fertilizer level followed by the same lower case letter are not significantly different at $P = 0.05$. Main effect values of a trait across N fertilizer levels followed by the same upper case letter are not significantly different at $P = 0.05$.

Year 1, as was the case for biomass in Year 1 (Table 2). The overall yearly maximum N accumulation did not exceed 47.2 kg ha⁻¹ (Year 2) and was only 6.5 kg N ha⁻¹ more than the lowest amount of N accumulated (Table 2). Because unfertilized but effectively nodulated soybean derives N mostly from N₂ fixation, the amount of fertilizer N applied to the wheat crop had no effect on above N accumulation by soybean (Table 1 and Table 3). Salvator and Sabbe (1995) reported less than 41% of N (25 mg N kg⁻¹ soil) from soybean residue was recovered by a grass crop grown on a fertile soil. Less than 10% of ¹⁵N-labeled soybean green manure was recovered by a tomato (*Lycopersicon esculentum* L.) crop (Thönnissen et al., 2000a), even though within 5 wk more than 70% of the soil-incorporated soybean had decomposed (Thönnissen et al., 2000b). We suspect much less of a N benefit for soybean cut for mulch or grazed. Soybean cut for hay leaving roots and a small amount of stubble may even cause net immobilization of soil mineral N (Bowen et al., 1988). Consequently, given that soybean aboveground N contribution was at most only 44 kg N ha⁻¹, the N benefit to a following winter wheat crop would be limited. Use of a forage-type soybean and extending the growth period before incorporation as a green manure could increase soybean biomass and the amount of aboveground N that would benefit the following winter wheat crop (Rao et al., 2005).

Winter Wheat Forage Responses

Biomass

An understanding of the effects (favorable and unfavorable) of soybean cropping on the productivity of winter wheat grown for forage is also needed to assess the feasibility of this double-crop system. Forage yields of winter wheat among summer management treatments were not consistent across the three successive years of the double-crop sequence. The significant summer management treatment × year interaction (Table 1) was due to low yield of wheat forage for the fallow NT and soybean mulch treatments within Year 1, the low yield of wheat forage for the soybean green manure treatment within Year 2, and a uniform forage biomass among the management treatments in Year 3 (Table 2). Wheat forage yields were affected more by year than treatment and ranged from 4.46 to 9.25 Mg ha⁻¹. Winter wheat forage yield was 5.44 Mg ha⁻¹ in Year 1 of the three successive years and corresponded to the greatest preceding soybean crop yield and the least amount of precipitation (114 mm less than 12-yr average) received between planting and the harvest of the wheat crop. These conditions probably reduced subsoil moisture and increased water deficit stress to the wheat crop. The best forage yield was not obtained in Year 2, when precipitation was normal, but was greatest in Year 3 (8.50 Mg ha⁻¹), with a 71-mm deficit from the 12-yr average. This may have been partly due to the lowest preceding soybean

crop yield and a favorable distribution of precipitation and average daily temperature in Year 3 that would promote late winter and early spring growth. Between January 1 and forage harvest on 21 April, Year 3 had 84 mm more precipitation and 15% greater growing-degree-days (base 0°C) than Year 2 (data not shown).

The response of winter wheat forage biomass to summer management was not consistent across N0 (0 kg N ha⁻¹) and N1 (112 kg N ha⁻¹) fertilizer levels. The interaction of these effects was significant because the relative biomass differences of each treatment for the two levels of N applied to winter wheat were not constant (Table 1 and Table 3). For example, the relative difference in biomass of wheat forage was 18% for summer fallow treatments compared to 46% for the soybean mulch treatment. Within each N fertilizer level, differences in winter wheat forage yields among treatments were not significant, but as expected the overall average of the N1 treatment produced 29% more biomass than the 6.0 Mg ha⁻¹ forage yield of the N0 treatment (Table 3). The limited return of N from the soybean forage was insufficient to match the winter wheat biomass response achieved by applying 112 kg N ha⁻¹ of fertilizer. Compared to the summer fallow treatments the presence of soybean as a green manure crop at even the N0 fertilizer level did not provide a significant N benefit to the following wheat crop. After 3 yr of growing soybean in the same plots the average winter wheat biomass of the soybean green manure and mulch treatments at N0 (7.58 Mg ha⁻¹) was nearly identical to the 7.57 Mg ha⁻¹ average of the other summer management treatments at N0 and 24% less than the N1 fertilizer level averaged across all treatments (data not shown).

Crude Protein

During the 3 yr, forage crude protein concentrations shortly after anthesis varied nearly 3.7-fold among the individual plots and ranged from 56 to 209 g kg⁻¹ with an overall average of 126 g kg⁻¹. About 22% of the wheat forage samples mostly from N0 plots (data not shown) and Year 3 (Table 4) had a crude protein concentration less than 105 g kg⁻¹, a forage crude protein level required for growing 225-kg medium-frame calves at an average daily gain of about 0.7 kg d⁻¹ (National Research Council, 1984). While there was a significant summer management treatment × year interaction (Table 1 and Table 2), differences in forage crude protein among summer management treatments in Year 1, but not Year 2 or Year 3, account for the significant interaction. When forage crude protein values were averaged across N fertilizer levels and management treatments, the values were significantly different and inversely related to forage biomass values (Table 2). As expected, forage crude protein levels of winter wheat fertilized with 112 kg N ha⁻¹ were greater than those for winter wheat grown without fertilizer N (Table 3). Inclusion of soybean as a double crop

Table 4. Biomass, forage crude protein, and aboveground N accumulated by soybean and wheat crops for three successive double crops (Year 1, 2001–2002; Year 2, 2002–2003; Year 3, 2003–2004). Nitrogen fertilizers \times year means (soybean, $n = 16$; wheat, $n = 24$) were averaged across management treatments. Values for the soybean crop were at initiation of grazing and those of the wheat crop were at harvesting for hay.

N fertilizer	Biomass			Crude protein			N accumulated		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
kg ha ⁻¹	Mg ha ⁻¹			g kg ⁻¹			kg ha ⁻¹		
Soybean									
0	1.75ab [†]	1.81ab	1.46b	139d	169c	199b	37.0b	47.3a	45.7ab
112	2.05a	1.50b	1.25b	141d	201b	227a	44.4ab	47.1ab	44.7ab
Winter wheat									
0	4.29d	6.13c	7.57b	131b	114c	84d	91d	111c	104cd
112	6.60bc	7.26b	9.42a	159a	139b	130b	166b	161b	195a

[†]Values within a trait of each crop followed by a different letter are significantly different at $P \leq 0.05$.

Table 5. Significance ($P > F$) values from the ANOVA of mineral N ($\text{NH}_4^+ + \text{NO}_3^-$), total N, and total C concentrations at soil depths of 0 to 15 and 15 to 30 cm at the onset (June 2001) and end (July 2004) of three successive double crops of soybean and winter wheat that was harvested for hay.

Effect [†]	0–15 cm depth			15–30 cm depth		
	Mineral N	Total N	Total C	Mineral N	Total N	Total C
	$P > F$					
Nitrogen (N)	0.0795	0.1254	0.1432	0.0834	0.1007	0.1864
Treatment (T)	0.3148	0.2082	0.0595	0.4969	0.0686	0.0025
N \times T	0.6881	0.7188	0.8380	0.2457	0.9526	0.9051

[†]Nitrogen, two levels of 0 and 112 kg N ha⁻¹ applied to winter wheat; treatment, six management levels consisting of summer fallow with conventional tillage, summer fallow with no-tillage, no-till soybean grazed, no-till soybean hay, green manure crop of no-till soybean, and mulch crop of no-till soybean.

did not benefit the crude protein concentration of the following winter wheat forage crop.

Nitrogen Accumulation

Averaged across both N fertilizer treatments, N accumulation by winter wheat grown in the fallow CT plots was greater than that in the soybean mulch plots in Year 1 and the grazed soybean NT plots in Year 3. Despite having the lowest forage crude protein concentration, overall year averages of aboveground N accumulation by winter wheat differed among years and was greatest in Year 3, reflecting the abundant forage yield seen that year (Table 2). The winter wheat N application \times summer management treatment interaction for N accumulation by winter wheat was not significant, but main effects of N application and summer management treatments were significant (Table 1 and Table 3). The year \times N application interaction was not due to any crossover response but was partly associated with a relatively high N₀ biomass yield in Year 2. The increase in N accumulation in the fallow CT in Years 1 and 3, but not Year 2, was a likely contributor to the year \times summer management interaction. Each year about 116 kg N ha⁻¹ accumulated by the winter wheat forage was derived from the soil in the unfertilized CT and NT treatments. An average of an additional 71 kg N ha⁻¹ was recovered each year in winter

wheat forage when these same summer management treatments were fertilized each year with 112 kg N ha⁻¹ (N1), corresponding to an apparent fertilizer N use efficiency of 63%. If the entire additional aboveground N input derived from the soybean manure and mulch (each about 48 kg N ha⁻¹ yr⁻¹) is included, then fertilizer N use efficiency for winter wheat receiving N fertilizer decreases to 44%. There was no benefit from the soybean crop in terms of winter wheat aboveground N accumulation whether or not fertilizer N was applied (Table 3).

Soil Nitrogen and Carbon

Except for one case, soil mineral N ($\text{NH}_4^+ + \text{NO}_3^-$), total N, and total C measured following the last wheat harvest of the three sequential years of double-cropping soybean and winter wheat forage were not significantly different due to amount of N applied to the wheat crop, summer management treatment, or the interaction of these effects (Table 5). The one unexpected exception was less total C measured in the 15- to 30-cm soil depth of the soybean crop cut for hay compared to the soybean manure and mulch treatments (Table 6). We believe contributions of soybean biomass were insufficient and the amount of time for NT to have a positive effect on soil organic matter levels was inadequate to observe any substantial change in the soil concentration of total N and total C. The Norge silt loam soil bulk density was 1.44 g cm⁻³ for the 0- to 15-cm depth (data not shown) and based on July 1999 soil analyses would contain about 1.71 Mg ha⁻¹ total N and 18.0 Mg ha⁻¹ total C. An upper limit for the contribution of aboveground soybean N to the soil N pool would be 133 kg ha⁻¹ after 3 yr, which is less than 8% of the soil total N pool in the upper 15 cm of soil. This upper limit is for the soybean manure treatment and assumes soybean N was derived entirely from N₂ fixation and after 3 yr all incorporated N remained in the soil. Similarly for the soybean manure treatment, the contribution of aboveground biomass C after 3 yr was 1.96 Mg ha⁻¹, or less than 11% of the total C pool in the upper 15 cm of soil, and does not account for substantial losses of C due to mineralization of the soil-incor-

Table 6. Least-square means of mineral N ($\text{NH}_4^+ + \text{NO}_3^-$), total N, and total C concentrations at soil depths of 0 to 15 and 15 to 30 cm at the end (July 2004) of three successive double crops of soybean and winter wheat that was harvested for hay.

Treatments [†]	Mineral N			Total N			Total C		
	N0	N1	Mean	N0	N1	Mean	N0	N1	Mean
	mg kg ⁻¹			g kg ⁻¹			g kg ⁻¹		
0–15 cm depth									
Fallow CT	4.9	11.1	8.0	0.669	0.719	0.694	7.35	7.91	7.62
Fallow NT	5.8	7.0	6.4	0.691	0.773	0.732	7.48	8.57	8.02
Graze NT	7.0	10.2	8.6	0.663	0.728	0.696	7.14	7.89	7.51
Soy hay NT	6.6	7.4	7.0	0.681	0.694	0.687	7.23	7.38	7.30
Soy manure	5.4	7.7	6.5	0.748	0.741	0.744	8.40	8.41	8.40
Soy mulch	7.8	14.2	11.0	0.726	0.857	0.791	8.31	9.62	8.96
Mean	6.2	9.6		0.696	0.752		7.65	8.29	
15–30 cm depth									
Fallow CT	5.1	14.0	9.5	0.577	0.612	0.595	6.31	6.64	6.47BC [‡]
Fallow NT	5.8	7.0	6.4	0.605	0.632	0.619	6.59	7.00	6.79ABC
Graze NT	5.9	10.1	8.0	0.579	0.614	0.596	6.33	6.48	6.40BC
Soy hay NT	5.3	8.3	6.8	0.586	0.591	0.589	6.27	6.33	6.30C
Soy manure	4.5	12.5	8.5	0.613	0.661	0.637	6.85	7.52	7.18AB
Soy mulch	5.9	11.2	8.5	0.630	0.656	0.643	7.25	7.44	7.35A
Mean	5.4	10.5		0.598	0.628		6.60	6.90	

[†]CT, conventional tillage; NT, no tillage.

[‡]Main effect values of a trait across N fertilizer levels followed by the same upper case letter are not significantly different at $P = 0.05$.

porated aboveground biomass. The input of aboveground soybean N and C would be substantially less for the other soybean treatments. Extending the seasonal growth period could substantially increase late-maturity soybean cultivars' contribution to aboveground N and C inputs to the soils in the southern Great Plains. The extended season would still provide an opportunity to plant wheat, provided precipitation is sufficient to support additional soybean productivity (Rao et al., 2005).

CONCLUSIONS

Productivity of soybean in a wheat-soybean forage double-crop system in the southern Great Plains was marginal when grazing or harvest of the soybean was initiated soon after growth stage R5. Yearly aboveground N accumulation of soybean N averaged about 44 kg ha⁻¹ and failed to offer any N benefit to the following winter wheat crop or significantly enhance soil N or C content after 3 yr, even when the soybean was soil incorporated as a green manure. Alternatively, use of soybean as a double crop did not adversely affect the productivity of the following winter wheat crop that was harvested for hay in the spring. But growth of soybean during the summer could deplete soil water and reduce autumn growth of winter wheat such that producers wishing to graze wheat in the autumn would have to delay grazing and reduce pasture stocking. Further research, however, is needed to determine if this occurs. Unless producers are willing to accept the low productivity of soybean as a double crop with winter wheat, wide

adoption of this dryland double-crop forage system among producers in the southern Great Plains is unlikely.

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